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Research on the problem of landmines and explosive remnants of war worldwide and methods of demining

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Abstract
The study addresses the global issue of landmines, with a particular focus on the challenges in Bosnia and Herzegovina. The research is grounded in precise data and facts from institutions and accredited demining organizations. The study further concentrates on innovative and highly effective detection methods, specifically for areas with challenging topography like Bosnia and Herzegovina, concluding with an innovative application of GPR and LiDAR radar technologies. Additionally, it explores the most effective method for mine removal, and mechanical demining, providing a detailed overview of the operation and characteristics associated with this approach. Conclusively, the study proposes the most efficient solution: a combined system of flails and tillers that alternately complement each other to achieve complete mine clearance.

Keywords: Landmine, UGV (unmanned Ground Vehicle), Mechanical demining, Landmine detection system, LiDAR, GPR (Ground penetrating radar), Flail wheel, Tiller

1. Introduction

The persistent global threat of landmines and unexploded ordnance (UXO) poses severe risks to civilians, economic stability, and post-conflict recovery efforts, with Bosnia and Herzegovina representing one of the most heavily mined regions in the world. Various types of landmines, including anti-personnel and anti-tank mines, present unique challenges for detection and clearance. Anti-personnel mines, particularly blast, fragmentation, and directional fragmentation types, are often designed to target individuals, while anti-tank mines are engineered to withstand greater pressure and pose a substantial hazard to vehicles and machinery.

Modern advancements in detection technologies, such as Ground-Penetrating Radar (GPR) and LiDAR, offer enhanced capabilities in identifying buried mines with high accuracy, helping to reduce manual intervention risks. Mechanical demining methods, which integrate tools like flails and tillers, have proven highly effective in physically neutralizing mines, offering versatility in different terrains. The innovative combination of flails and tillers within a single demining system capitalizes on the strengths of both tools, achieving increased clearance depth, efficiency, and adaptability to various soil types. This comprehensive approach to demining, combining advanced detection technologies with robust mechanical solutions, addresses the complexities of mine clearance, offering safer, more reliable solutions for global and localized demining efforts.

2. Landmine threat

According to United Nations data, there are currently over 100 million landmines planted in more than 85 countries worldwide, with the vast majority laid within the past 80 years. Most of these mines are anti-personnel mines, resulting in 15,000 to 20,000 casualties annually, with a mortality rate exceeding 50% due to the lack of immediate adequate assistance. The twelve most landmine-contaminated countries in the world, according to the United Nations (UN), are Afghanistan, Angola, Bosnia and Herzegovina, Cambodia, Croatia, Eritrea, Iraq, Mozambique, Namibia, Somalia, Nicaragua, and Sudan. Together, these countries account for more than 50% of the world's contaminated minefields [1].

2.1. The problem of landmines in the world

Global conflicts during the 20th century and the first half of the 21st century have left behind one of the most lethal weapons of all time: landmines. These mines represent the most inhumane and indiscriminate method of killing. For over 80 years, countries worldwide have been contaminated with unexploded landmines and ordnance. The development of these devices has continually advanced, making them even deadlier—even during the removal and demining processes.

Originally, landmines were created for offensive warfare, intended to prevent enemy reentry or to protect specific locations or fortifications. Early forms date back to antiquity, with significant advancements in offensive warfare emerging with the discovery of gunpowder and its deadly applications. Over the years, through successive wars, landmines have evolved to become increasingly lethal and resilient, purposefully designed with one goal: to kill. They have reached a level of resilience that even natural conditions do not affect their lifecycle; they are engineered to remain dangerous and deadly until they make contact with a person. More than 85 countries around the world are affected by the problem of landmines, posing a significant risk to the daily safety of civilians and innocent people who are at risk of becoming victims each day.

2.2. The problem of landmines in Bosnia and Herzegovina

Nearly 30 years after the end of armed conflicts, Bosnia and Herzegovina remains among the countries facing a significant landmine threat. Landmines and unexploded ordnance (UXO) still pose a grave danger to the population and impede access to numerous resources. The conflicts on Bosnian territory from 1992 to 1995 resulted in extensive mine-contaminated areas, making it difficult to estimate the exact number of mines laid or remaining. This challenge is due to incomplete documentation from various military and paramilitary organizations active during the war, with some records lost or destroyed in military operations.

According to estimates by UNICEF, MAC, and the U.S. Department of State dating back to 1996, between 1,000,000 and 6,000,000 mines were placed on Bosnian territory. This figure includes mines planted by military and paramilitary formations, as well as international forces operating in Bosnia and Herzegovina during that period. From 1996 to 2002, a total of 18,228 incidents were registered, with more than two-thirds occurring in the Federation of Bosnia and Herzegovina.

Estimates by BHMAC (Bosnia and Herzegovina Mine Action Centre) indicate that suspected mine-contaminated area was 4,000.2 km² (8.2% of the total land area). According to BHMAC data as of December 31, 2021, the size of mine-contaminated or suspected hazardous areas across Bosnia and Herzegovina stands at 922.37 km² (1.8% of the total land area), with the Federation of Bosnia and Herzegovina being more heavily affected, covering 727.28 km² (78% of the total contaminated area in the country).

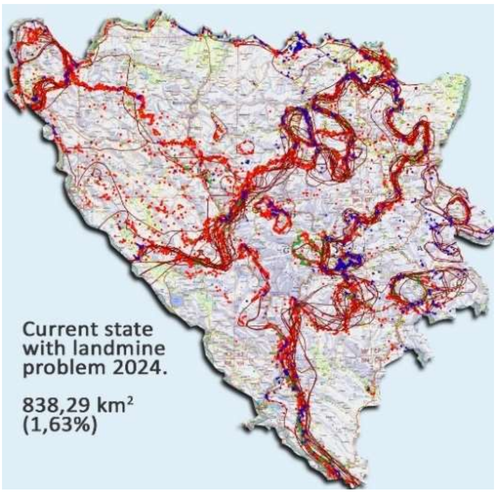

Figure 1. Landmine map of Bosnia and Herzegovina [5]

2.3. Statistics of "hidden killers"

Although these "hidden killers" have evolved, their continued development—despite prohibitions and conventions—conveys the same fundamental message. The solution for countries affected by mine-contaminated areas is to eliminate these dangers and make them safer through mine action programs, which increase awareness of the threat, remove the hazards, and provide holistic support to victims and their families.

The understanding of landmine issues today is much more advanced than it was in 1993 or 1996 when the landmine ban convention was established. The problem of mine contamination is now viewed not only in terms of the numbers planted but also as an issue impacting many facets of daily life, including human safety and economic viability, due to the unusable nature of contaminated land.

Key points regarding demining:

- Efficiency of demining: This remains a persistent challenge, nearly insurmountable compared to the volume of mines laid. Demining is estimated to take one hundred times longer than the placement of mines.
- Global mine count: Over 100 million anti-personnel mines are laid worldwide.
- Estimated cost: More than $33 billion is needed to clear these mines (assuming no new mines are laid).
- Timeframe: At the current removal rate, it would take 100 years to clear all mines.
- Casualties: Anti-personnel mines cause approximately 70 casualties per day, around 20,000 per year.
- Impact on children: Over 300,000 children have been harmed by mines.
- Mortality rate: More than 50% of mine victims die en route to the hospital.
- Demining vs. Laying mines: For every hour spent laying mines, 100 hours are needed for removal.
- Cost disparity: Producing a mine costs as little as $3, but it takes more than $1,000 to remove.
- Risk of demining: The demining process is extremely dangerous, with one accident occurring for every 1,000 to 2,000 mines removed.

2.4. Ban of landmines

Reports by the Landmine Monitor, UN, and GICHD describe anti-personnel mines as a "widespread" and long-term environmental contaminant and a significant driver of mortality rates. Anti-personnel mines lack self-destruct mechanisms, endangering millions of lives daily. These are the primary reasons behind the ban on their production and use. In Ottawa in 1997, an international treaty known as the "Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Anti-Personnel Mines and on their Destruction" was inaugurated, with 122 countries initially signing on. This convention placed anti-personnel mines on the list of banned weapons under international humanitarian law, aligning them with other weapons of mass destruction, such as biological and chemical weapons (war gases). Since then, 164 nations worldwide have ratified or joined the Convention, including the vast majority of countries affected by anti-personnel mines.

Bosnia and Herzegovina has been a signatory to the Ottawa Convention since March 1, 1999. Through domestic mobilization and increased international support, Bosnia and Herzegovina has destroyed its entire stockpile of anti-personnel mines, made significant progress in clearing mine-contaminated areas, and provided substantial support to victims from 1999 to the present.

3. Classification of landmines

A mine is an explosive weapon concealed below or camouflaged on the ground, designed to destroy or disable enemy targets, ranging from combatants to vehicles and tanks, as they pass over or near it. Mines are primarily classified into:

1. Anti-personnel mines (AP)
2. Anti-tank mines (AT)

Mines can also be classified by their activation mechanisms:

1. Pressure-activated mines (triggered by pressure)

2. Mines with alternative detonation mechanisms (such as tripwires, electrical circuits, or electronic fuzes) [1].

Due to the structure of this work, we will limit our focus to the basic classification of mines, which also includes various types of mines that are detonated through different mechanisms.

3.1. Anti-personnel mines

Anti-personnel mines are a type of pressure-activated mines designed for use against people, unlike anti-tank mines, which are intended for vehicles. They are often engineered to injure rather than kill victims, thereby increasing the logistical (mainly medical) support needed by the enemy forces encountering them. Some types of anti-personnel mines can also damage the treads of armored vehicles or tires on wheeled vehicles. These mines are deployed similarly to anti-tank mines, in static "minefields" along national borders or to defend strategic locations. However, they differ from most anti-tank mines in their smaller size, allowing large numbers to be deployed over extensive areas. This deployment can be done manually, via dispensers on ground vehicles, or from helicopters or planes. Alternatively, they may be scattered using specialized projectiles [1].

Anti-personnel mines can be classified as follows:

1. Anti-personnel pressure mines – activated by shockwave overpressure.
2. Anti-personnel fragmentation mines – fragmenting upon activation.
3. Anti-personnel directional fragmentation mines – designed for targeted dispersal.

3.1.1 Anti-personnel blast mines (shockwave pressure effect)

When a person steps on a landmine and activates it, the mine's main charge detonates, creating a shockwave of hot gases traveling at extremely high velocity. This shockwave generates immense upward pressure, propelling the mine casing and any overlying soil upwards. Upon impact, the shockwave transfers this force to the victim's footwear and foot. This results in a significant compressive force on the victim's foot, with the blast often causing severe injury or amputation. Injuries vary depending on the main charge size, mine depth, soil type, and the manner of contact (e.g., full or partial foot placement on the mine).

Different soil types transmit varying energy amounts upwards; saturated clay-like soil, for example, transmits more energy. Higher explosive charges release substantially more energy, extending the shockwave impact up the leg, sometimes causing traumatic amputation as high as the knee. Secondary injuries are often from materials displaced by the explosion, including soil, stones, footwear fragments, and foot bone shards, which create additional wounds similar to other explosive fragmentation effects. Special footwear, such as combat boots or "demining boots," provides only limited protection from the destructive force of mines, with foot loss being a typical outcome [3].

Figure 2. Type of Anti-personnel (blast) mine; Model VS-50

3.1.2 Anti-personnel fragmentation mines

While anti-personnel mines are designed to cause severe bodily injury, often leading to surgical amputations of the lower limbs, fragmentation mines are intended to disperse fragments over a broad area, primarily causing shrapnel injuries. These mines are typically larger and heavier than anti-personnel mines, as they contain a substantial metal casing (weighing several kilograms) that produces the fragments. One advantage of these mines is that they are relatively easy to detect due to their high metal content - though this only applies in areas where the soil is not overly contaminated with iron materials or other metal waste.

Figure 3. Type of Anti-personnel (fragmenting) mine; Model: PMR-3

Fragmentation mines are more effective and lethal on the battlefield due to their broader impact radius, with the potential to wound multiple individuals simultaneously. Fragments from these mines can also partially disable armored vehicles by damaging suspension systems and tires, and in unarmored vehicles, they can significantly harm internal components and occupants.

3.1.3 Anti-personnel directional fragmenting mines

These mines differ from other types in that they are designed to direct their fragments in a limited arc. They are positioned so that the explosion is aimed toward a target area, away from friendly forces. This design allows forces to protect themselves by placing these types of mines near their own positions, but oriented toward the enemy. They are typically triggered in a conventional manner, either by a tripwire or through command detonation [4].

3.2. Anti-tank mines

Unlike anti-personnel mines, anti-tank mines typically contain a larger amount of explosive charge, making them exceptionally lethal. Their primary purpose is to destroy or damage tanks or armored combat vehicles. The fuse design is specialized to activate only upon contact with a vehicle, by remote access from a monitored distance, or if there is an attempt to tamper with the mine for removal. The first anti-tank mines appeared toward the end of World War I as a countermeasure to British tanks. These initial forms were quite primitive; however, anti-tank mines saw significant expansion and development during World War II, where their effectiveness on the battlefield led to the formation of the first demining units within armies, spurring mutual study among opposing forces. The most heavily contaminated anti-tank minefield recorded to date was on the Eastern Front in World War II by the Soviet Army, reporting a total of 503,663 anti-tank mines, with an average density of 1,500 mines per kilometer.

With the advancement of the global military industry, we now distinguish several types of anti-tank mines:

1. Anti-tank blast mine - based on the impact of shockwave overpressure.
2. Anti-tank shaped charge mine (with Explosively Formed Projectile - EFP).

3.2.1 Anti-tank blast mine (based on shockwave effects)

Anti-tank blast mines, or mines activated by shock waves, function and are triggered similarly to anti-personnel blast mines. The key differences lie in the amount of explosive charge and the activation mechanism. Anti-tank blast mines typically contain between 4 and 11 kg of various explosive charges, and the pressure needed to trigger them is much higher - generally, a weight over 100 kg is required. These mines are primarily intended to target and destroy vehicles, whether armored or unarmored, although certain variants can be triggered by human activity, especially during mine removal or demining processes. It is rare to find cases where one anti-tank mine is placed directly above or next to another to increase explosive power and lethality. They are designed to be placed precisely along the width of a tank's track or the wheelbase of an (un)armored vehicle [1].

Figure 4. Anti-tank destructive mine; Model TM-46

3.2.2 Anti-tank shaped charge mine (based on Explosively Formed Projectile)

An Explosively Formed Penetrator (EFP), also known as an explosively formed projectile, is a specialized type of shaped charge designed to effectively penetrate armor from a much greater distance. As its name suggests, the explosive charge deforms a metal plate into a rod-like shape and propels it toward the target at high velocity. Originally developed in the 1930s by American oil companies as perforators for oil wells, EFPs were later adapted for military use during World War II.

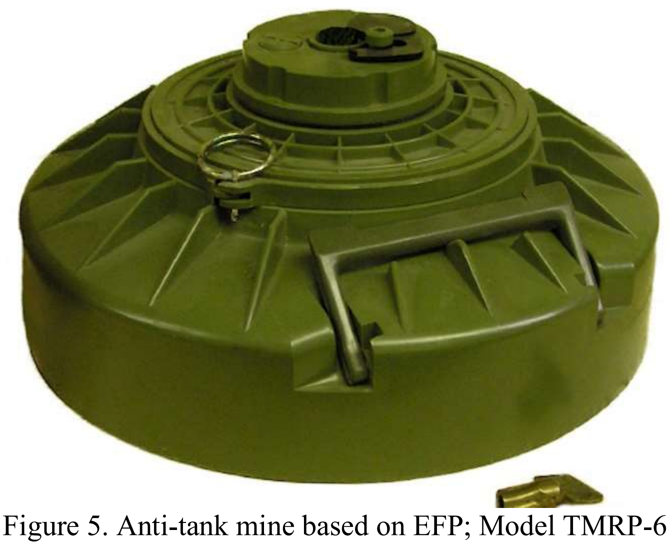

Figure 5. Anti-tank mine based on EFP; Model TMRP-6

3.3. Unexploded ordnance (UXO)

Unexploded Ordnance (UXO) is a term used to describe explosive devices that were prepared for use in armed conflict. This includes munitions that may have been fired, dropped, or launched but failed to detonate—military terminology refers to this as "Unexploded ordnance." It is often abbreviated as "UXO," "NUS" (from the Bosnian term "Neeksplodirana Ubojna Sredstva"), or "ERW" (which stands for Explosive Remnants of War).

UXO is not exclusively linked to conflict zones from World War I and World War II; areas such as military training centers, weapons production sites, and bombing ranges can also contain significant quantities of explosive ordnance buried underground or submerged underwater—even on coastal cliffs. UXO also refers to explosive devices that were never used during armed conflict and have been left behind or discarded. When explosive devices are discovered, they are sometimes destroyed in controlled explosions, although accidental detonations can also occur [6].

Unexploded ordnance (UXO) contains unstable compounds that become increasingly sensitive over time due to aging. The expert advice is that if you ever encounter a suspicious object, do not touch it; instead, call the police or specialist services for assistance. The most obvious danger of encountering UXO is an explosion. However, some items dating back to World War I may have been associated with chemical weapons, and if they have been buried and left undisturbed for a long time, they could potentially cause environmental or soil contamination. The size or shape of any UXO does not indicate its potential danger; small objects can kill and maim if handled improperly - it's better to be safe and take the appropriate precautions.

As with most things, there are many exceptions to the rule, but generally, UXO can be categorized into two main groups [10,11,12]:

1. Air-delivered explosive ordnance.
2. Military explosive ordnance (items that have been fired, lost, dropped, buried, burned, or otherwise disposed of).

Essentially, unexploded ordnance is primarily classified based on its mass and the quantity of explosive filling:

1. Small unexploded ordnance.
2. Medium-sized unexploded ordnance (such as artillery munitions).
3. Large mass unexploded ordnance (explosive devices with a filling mass of up to and exceeding 500 kg; e.g., aerial bombs).

3.3.1 Small-size unexploded ordnance

Small unexploded ordnance (UXO) is one of the most prevalent forms of UXO found on battlefields worldwide, with estimates suggesting that over 65% of contaminated areas are comprised of this type. The contamination from this type of UXO is primarily due to its usability on the battlefield, where a significant number are left behind or lost, thereby becoming increasingly dangerous over time. These are defined as explosive devices with a small amount of explosive filling and smaller physical dimensions. They contain explosive filling of less than 500 grams and rely on a combination of explosive and fragmentation effects to incapacitate personnel and vehicles.

Examples include the following: hand grenades, mortar projectiles, 40mm anti-aircraft ammunition, and cluster munitions.

Figure 6. Example of small-size UXO

3.3.2 Unexploded ordnance of medium size

Medium-sized UXO is the second most common type of UXO, involving explosive devices with charges ranging from 1 to 20 kg. These devices rely on a combination of fragmentation and explosive effects to disable vehicles and personnel. This category includes certain types of projectiles, artillery shells, and smaller rockets. These explosives are typically encased in metal shells, making them particularly hazardous if left on the ground unexploded, where they pose a threat if accidentally encountered. Exposure to moisture leads to metal oxidation and corrosion, which can make them even more deadly if disturbed or moved from their original position. The standard method for removing UXO of this type is to destroy it in a controlled manner at a safe location under supervised conditions.

Figure 7. Example of medium size UXO

3.3.3 Unexploded ordnance of large mass

Large-mass UXO is one of the most lethal and dangerous types of UXO found in all war-affected countries. A notable aspect of this UXO type is its "elusiveness," as such threats are typically discovered by chance, often during excavation for sewage or water pipes or the foundation work of buildings, when an unidentified explosive device is encountered. This category includes explosive devices with a charge of 500 kg or more, with WWII-era aerial bombs being the most common. The unique risk with this UXO type lies in the potential consequences of detonation or relocation, as it can endanger an area within a 500-meter radius, with severe repercussions. Consequently, the disposal or removal of large-mass UXOs, particularly aerial bombs, is handled with extreme caution.

Figure 8. Example of large mass UXO

4. Demining (process of landmines removal)

Demining is the process of removing landmines from an area, making it safe for human use. Landmines are explosive devices that can cause severe injuries or death to people and animals who trigger them. Often used in wars and conflicts, they remain a threat long after hostilities have ended. According to the „Landmine Monitor 2020“ report, 5,554 people were harmed by landmines and other explosive remnants of war in 2019, 43% of whom were children. Different demining methods are used depending on the type, location, and quantity of landmines, as well as available resources and technology. Conventional methods include the use of probes, metal detectors, dogs, and mechanical devices to locate and remove landmines. Developing methods involve technologies like electromagnetic sensors, vapor detection, dispersed explosives detection, acoustic/seismic detection, unmanned ground vehicles, and drones.

Demining can serve military or humanitarian purposes. Military demining focuses on quickly and effectively clearing a path through a minefield, using tools like mine plows and blast waves. Humanitarian demining aims to remove all landmines to a specific depth, ensuring that the area is completely safe for civilian activities. Specialized organizations perform humanitarian demining, following international standards and guidelines. This process is essential for reducing the risk of casualties, restoring access to land and infrastructure, enabling socio-economic development, and promoting peace and security.

The history of demining dates back to World War I, when soldiers used rudimentary tools like bayonets, knives, and probes to locate and remove mines. Since then, demining has evolved into a more sophisticated and systematic activity involving a range of technologies such as metal detectors, ground-penetrating radar, robots, drones, and trained animals like dogs and rats. However, demining remains a challenging and costly endeavor due to factors like the type, age, and condition of mines, terrain, weather, vegetation, resource availability, and security considerations.

Demining faces obstacles as both a humanitarian necessity and a technical challenge. Millions of landmines remain scattered across more than 50 countries, causing death, injury, displacement, poverty, and environmental degradation. While demining is crucial for protecting lives and livelihoods, restoring peace and stability, enabling development and reconstruction, and upholding human rights and dignity, it faces challenges such as funding shortages, lack of coordination, insufficient data, limited standards, innovation needs, and political will.Therefore, demining requires not only technical solutions but also political strategies to address the root causes of the landmine problem and prevent its recurrence.

Global demining organizations are dedicated to clearing landmines and other explosive remnants of war in conflict-affected areas. They also provide humanitarian aid, risk education, and advocacy for the rights of victims and survivors. According to Landmine Monitor 2021, more than 60 countries and territories remain contaminated with mines, posing a serious threat to the safety and livelihoods of millions. These organizations work with local communities, governments, and international partners to implement effective and sustainable mine action solutions. Leading organizations in this field include Halo Trust, Mines Advisory Group, Norwegian People’s Aid, Danish Demining Group, and Handicap International.

4.1. Most effective methods for detection and removal of mines and unexploded ordnance (UXO)

Mine detection is the process of locating and identifying the presence of landmines or other explosive devices on land, in water, or elsewhere. This process uses various technologies and techniques to detect potentially dangerous devices and reduce the risk of injury or death. Detection often involves metal detectors, vibration sensors, or other specialized equipment that can identify the presence of metal or materials characteristic of mines. This is a crucial step in the demining process or in ensuring safety in areas with landmine risks. As technology advances, new methods and approaches in mine detection are continually developed, incorporating diverse sensor methods. Alongside technological advancements in detection methods, removal techniques have significantly improved in efficiency due to better and more precise detection. Mine removal involves safely removing or disabling mines or other explosive devices placed on land, in water, or elsewhere. The goal of this process is to minimize the risk of explosions and protect people, vehicles, and property from harm caused by mines.

The interdependence of detection and removal systems is crucial for the overall outcome and the success rate in clearing areas of mine-explosive remnants, especially in humanitarian demining, where UN standards require a 99.6% demining success rate. In light of this, the following paper will discuss several detection and removal methods that have proven highly effective in the field.

4.2. Methods for detecting mines and UXO

Mine Detection is the process of locating and identifying the presence of mines or other explosive devices placed on land, in water, or elsewhere. This process employs various technologies and techniques to detect potentially hazardous devices, thereby reducing the risk of injury or death. Mine detection typically involves the use of metal detectors, vibration sensors, or other specialized equipment capable of identifying the presence of metal or other materials characteristic of mines. This is a crucial step in the demining process or in securing areas at risk of mines. With advancements and refinements in technology, continuous work is being done on new methods and approaches for mine detection across different sensing methods.

The primary classification of detection methods, as shown in the following table, includes [7,8,9]:

1. Biological (biosensor-based),
2. Electromagnetic,
3. Optical,
4. Acoustic,
5. Nuclear,
6. Mechanical.

4.2.1 Biological (biosensor) method of mine detection

The biological method of mine detection is a technique that utilizes living organisms to identify the presence of mines or explosive devices in a given area. These organisms possess highly developed senses, such as smell or sight, enabling them to detect specific odors or signals associated with mines. Biological detection methods are often employed due to the high reliability of living organisms as detectors, their ability to quickly search large areas, and the relatively low cost compared to other detection techniques. However, these methods require training and maintenance of the organisms and ensuring their safety throughout the detection process. This method includes the use of dogs, rodents, bees, plants, and bacteria.

Figure 9. Biological landmine detection with trained dogs

4.2.2 Electromagnetic methods for mine and UXO detection

Electromagnetic detection methods use electromagnetic principles to identify objects or materials on or beneath the ground surface. These methods are widely applied in fields such as mine detection, geophysical research, archaeology, and geology. The principle of electromagnetic detection is based on changes in the electromagnetic field when materials with different electrical properties are present in the ground or underwater. These field changes can be registered and analyzed to identify targets of interest, such as minefields or archaeological remains. Electromagnetic detection methods employ various techniques and instruments, including Ground Penetrating Radar (GPR), electromagnetic mapping (EM), metal detectors, and other specialized devices.

Each of these techniques has its strengths and limitations and can be adapted to the specific needs of a survey or application. Their use is extensive and diverse, offering valuable information in multiple fields. These methods provide a quick and non-invasive way to detect mines, particularly below the ground surface, reducing the need for physical digging or probing. However, it is essential to consider the specifics of each method, including penetration depth, sensitivity to surrounding interference, and the requirement for trained personnel to achieve optimal detection efficiency.

Ground Penetrating Radar (GPR) detection operates by transmitting an electromagnetic signal into the ground and detecting the reflected signal with a receiver. The transmitter emits a pulse wave or continuous wave at a specific frequency. The receiver collects waves scattered back from discontinuities in permittivity. These discontinuities can be caused by buried objects like landmines (the useful signal) and natural irregularities in the soil (background noise). A key advantage of this technique is its ability to detect plastic objects buried underground, making it suitable for finding various types of landmines with different casings. GPR can also provide information on the target's depth and is relatively insensitive to small metal fragments.

However, GPR technology faces challenges. Microwaves are heavily attenuated in certain types of conductive soils, such as clay, making wet clay an extremely challenging environment for detection. Very dry soils, on the other hand, have reduced electrical contrast compared to plastic landmines, which can make these types of mines difficult to detect. Thus, while GPR offers valuable capabilities in detecting plastic-encased mines, its effectiveness depends significantly on soil conditions, which can limit reliability in some environments [1,2].

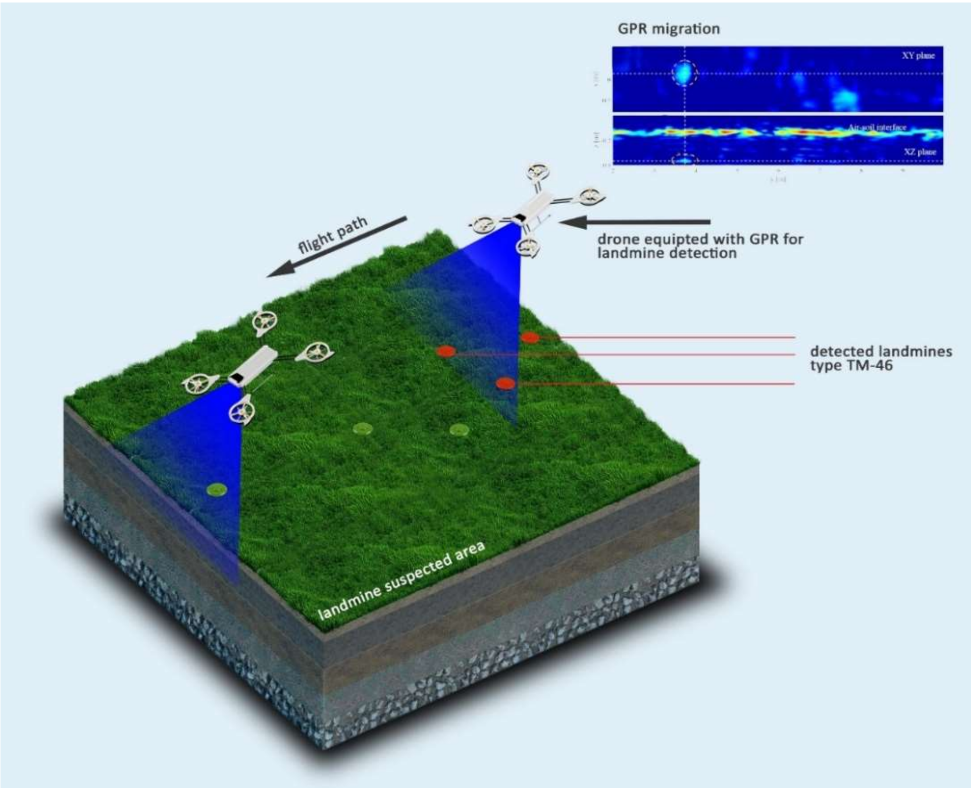

Figure 10. Visual presentation of landmine detection using GPR with drone scanning

4.2.3 Optical detection using LiDAR systems

LiDAR (Light Detection and Ranging) mine detection systems utilize laser beams to scan terrain in detail, enabling the identification of mines through a high-resolution, three-dimensional terrain map. LiDAR operates by emitting short laser pulses toward the ground and measuring the time it takes for them to reflect back. Based on this reflection time, LiDAR generates a detailed 3D image of the landscape. Variations in terrain elevation or the presence of objects, such as mines, cause differences in the reflection of the beam, enabling the identification of minefields. Simply put, the system identifies changes in surface structure that suggest the presence of mines or unexploded ordnance (UXO).

Mines or UXOs typically alter the terrain's topography or create distinctive shapes detectable through LiDAR technology. Advantages of LiDAR in mine detection include high resolution, rapid terrain scanning, the ability to penetrate through vegetation, and the capability to detect mines even beneath surface soil layers. This technology allows for swift identification of potentially hazardous areas and precise minefield mapping, aiding safe demining and restoration of affected areas. Moreover, combining LiDAR with other detection methods, such as metal detectors or ground-penetrating radar (GPR), can enhance detection accuracy and reduce the risk of missed mines. Due to its precision and reliability, LiDAR is increasingly valued as a tool in mine detection efforts, providing critical support in making affected areas safer [1].

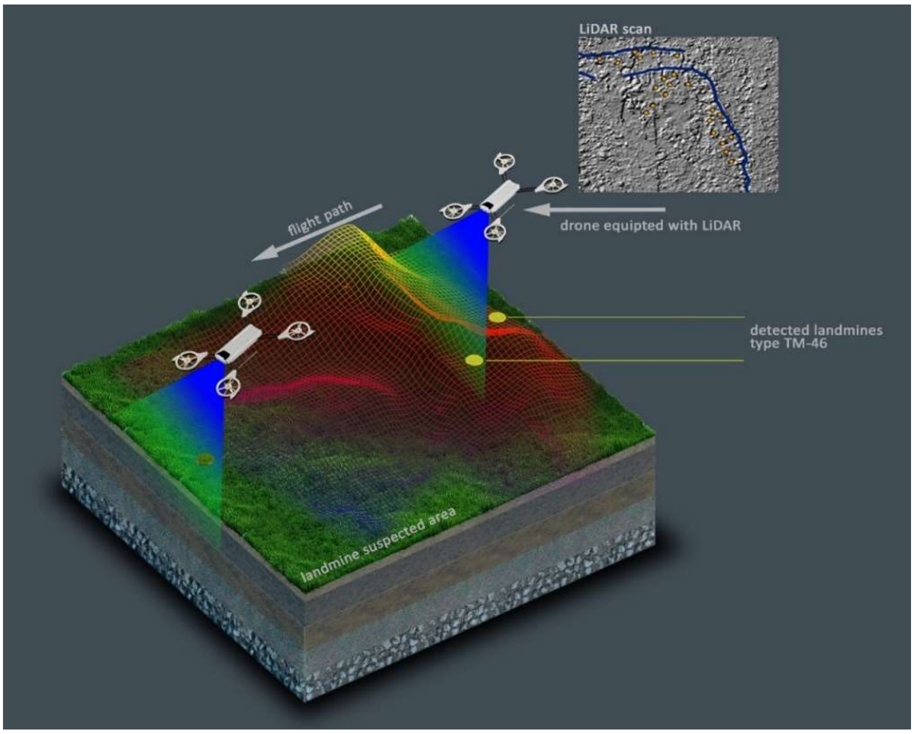

Figure 11. Visual presentation of landmine detection using LiDAR with drone scanning

4.2.4 Acoustic methods for detecting landmines and UXO

Acoustic methods for landmine detection are employed to identify the presence of mines in the field by analyzing sounds that they produce or reflect. These methods rely on distinctive acoustic signals emitted by a mine or the surrounding soil when exposed to certain external influences, such as impacts or vibrations. The operating principle of acoustic mine detection is based on detecting characteristic sounds generated when a mine responds to external stimuli, like mechanical vibrations or impacts. These sounds can be specific to certain types of mines or their components, enabling their identification using sensors or microphones. Acoustic waves present a viable means for detecting and identifying landmines. Common acoustic detection techniques include ultrasound and acoustic-seismic (A/S) methods.

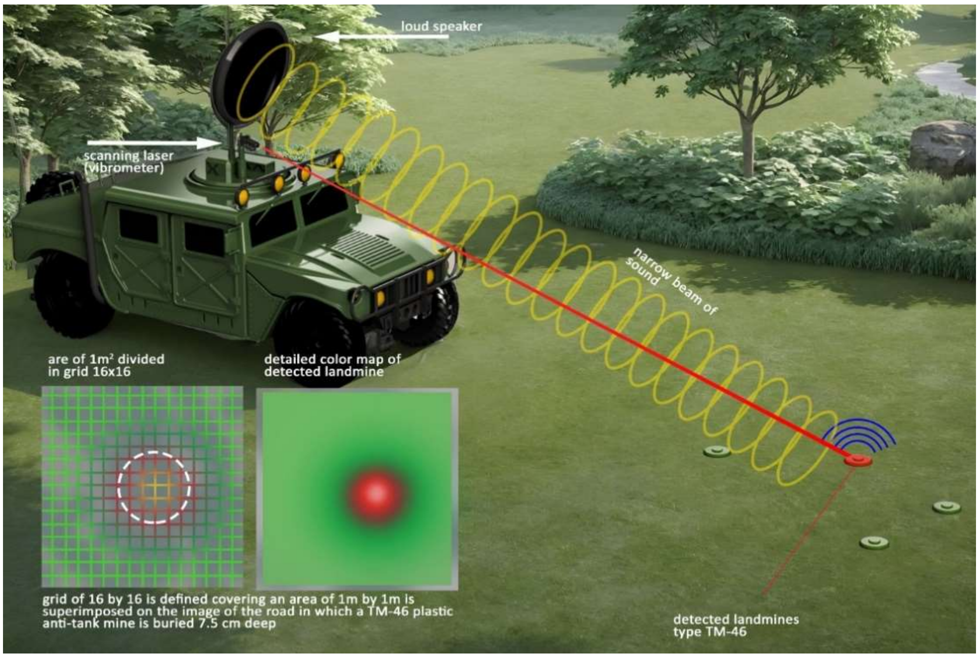

Figure 12. Visual presentation of landmine detection with acoustic method

4.2.5 Nuclear detection of landmines

Nuclear detection of landmines is an innovative approach in demining, used to identify the presence of explosive materials, including those in landmines, by leveraging nuclear reactions and characteristic radiation. This technique has a long history of research and development, dating back to the late 1940s and 1950s, when the application of nuclear physics in mine detection was first explored. Nuclear mine detection offers several advantages, including high sensitivity to the presence of explosives, rapid detection, and the ability to operate in diverse environmental conditions.

However, challenges remain, such as the requirement for highly specialized equipment and trained personnel, as well as the safety and environmental concerns associated with the use of nuclear materials. Despite these challenges, nuclear mine detection continues to hold promise as a valuable technique contributing to the advancement of safer and more efficient demining strategies in affected areas. Common nuclear detection techniques include Nuclear Quadrupole Resonance (NQR) and neutron-based methods.

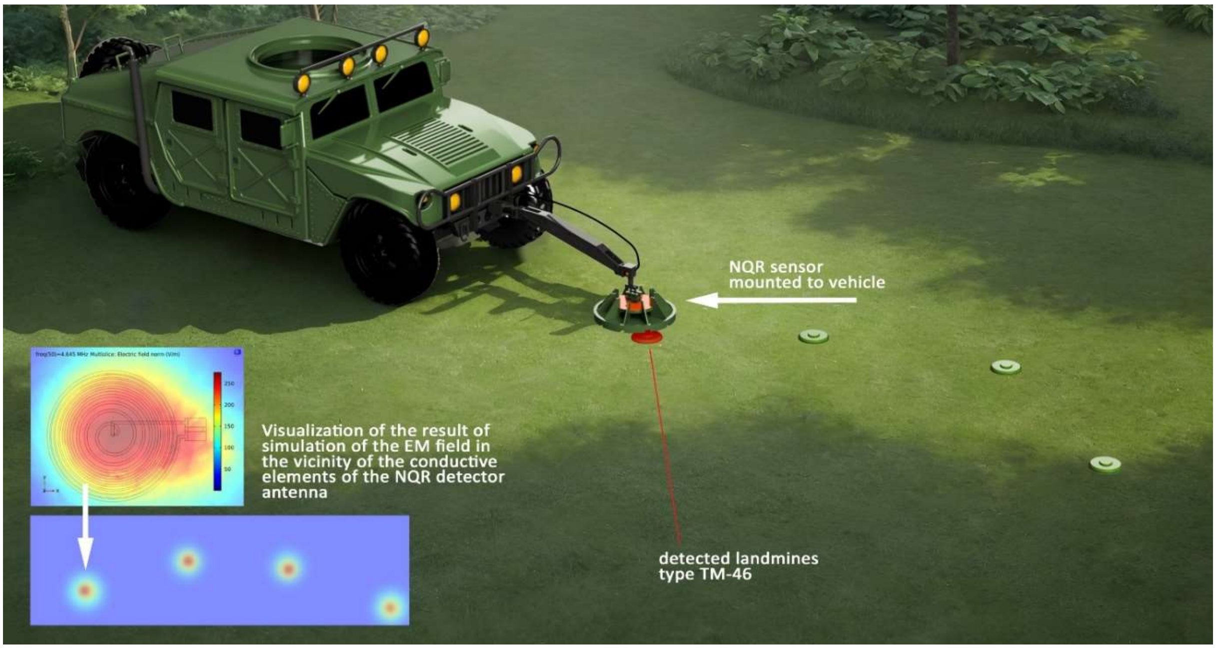

Figure 13. Visual presentation of landmine detection nuclear method, using NQR sensor

5. Mines and UXO clearance methods

Mine clearance is a complex process requiring high precision and specific safety measures to protect personnel in the field. For this purpose, mine clearance is generally divided into four main categories: manual clearance, mechanical clearance, explosive clearance, and clearance using robotic systems. The most efficient and effective method is mechanical clearance, which can, in certain aspects, be combined with robotic-assisted clearance.

Mechanical clearance of mines and unexploded ordnance (UXO) involves the use of appropriate and specialized equipment approved and regulated by the International Mine Action Standards (IMAS), as well as specific national mine clearance regulations and legislation, depending on the country facing the mine contamination problem. Mechanical mine clearance using demining machines is a critical technology in mine action operations. These demining machines are specialized vehicles or devices designed to search, identify, and clear mines from contaminated areas, either independently or in support of human intervention. They allow for faster, safer, and more effective clearance of mine-contaminated zones, reducing injury risks and accelerating the demining process.

Demining machines have a history that spans over a century, with early adaptations observed in tanks from World War I and II, repurposed to clear pathways for combat. In a military context, the objective was to neutralize enough hazards to ensure the relative safety of advancing troops, even if some risks remained acceptable. Today, various demining machines are utilized in Humanitarian Mine Action (HMA). Some are designated as “clearance machines,” suggesting the capability to remove all explosive hazards to a certain depth.

However, no machine that interacts with the ground can reliably achieve this. Machines that excavate and sift through soil before manual inspection can render areas safe, but this method tends to be slower, more costly, and environmentally damaging compared to manual clearance, particularly over large areas. In high-risk zones, such as trenches or destroyed buildings, machines like excavators and screens can effectively manage hazards while minimizing environmental damage.

Figure 14. Early examples of mechanical demining, 1st World War, Mark IV tank that has been adapted for mine clearance

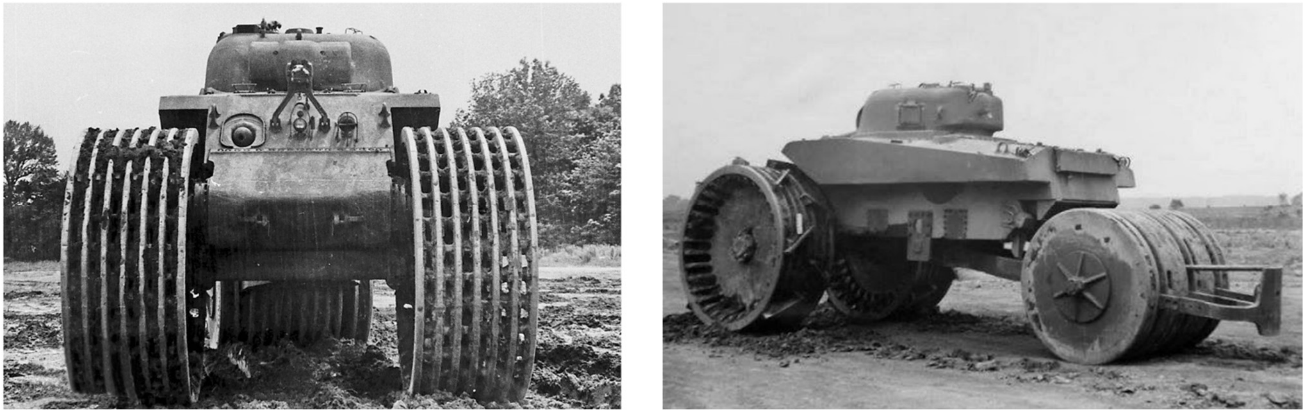

Figure 15. Mechanical demining during World War 2, T10 Mine Explorer, rebuilt tank M4A2

Nevertheless, demining machines have limitations: they often do not trigger all types of pressure-activated devices and may leave hazards in a more sensitive state. Additionally, they can inadvertently spread hazards over a wider area, complicating subsequent manual clearance efforts. The use of demining machines to expedite operations at the expense of safety contradicts the goals of HMA (Humanitarian Mine Action). The capabilities of these machines must be thoroughly assessed based on anticipated hazards, inherent risks, and the actual costs of implementation. Claims regarding the efficiency of machines are often exaggerated, and manufacturer recommendations may not align with practical applications. Real-world trials, rather than merely ideal conditions, should inform the planning and utilization of machines to understand their limitations [1].

An objective assessment of machine limitations could have prevented issues such as the use of rotary mine rakes on compacted dirt roads. In such cases, tree roots beneath the surface of the road could become entangled in the rake's teeth, disrupting rotation and causing damage. Moreover, the presence of rocks or bedrock could result in mechanical damage to the machine or necessitate a reduction in processing depth. In sandy areas devoid of rocks and roots, the soil was reduced to a deep layer of fine dust, making it impassable for vehicles.

Consequently, all unexploded ordnance (UXO) and smaller explosive hazards remained buried in the dust, while larger threats could be displaced beneath the surface. As vehicles were compelled to veer off the road onto adjacent land, accidents ensued, particularly if a minefield lay hidden below. The machine's effectiveness in eliminating all explosive hazards was compromised, posing increased risks to civilians and escalating search and clearance operation costs.

Marketed as a "threat reduction machine on roads," its implementation, along with detailed search and clearance procedures, could potentially clear pathways. However, due to the deep layer of dust, anti-tank mines with minimal metal content went undetected. Nonetheless, cost-effective demining machines can indeed offer economical solutions and significantly accelerate the release of land when reasonably integrated with original search and clearance protocols.

Over the previous years, technological advancements have led to the development of increasingly sophisticated demining machines, which have become vital tools in the demining process worldwide. The removal of mines using demining machines represents a crucial tool in the fight against thretas such as landmines, providing a safe, efficient, and precise solution for clearing affected areas of mine hazards, saving human lives in the process.

6. Advancements in technology and demining machines

Technological advancements have enabled the development of various types of demining machines, including:

1. Armorded vehicles with mine detonation systems: These vehicles utilize heavy and robust systems for detonating mines, allowing for the safe destruction of mines while keeping the vehicle protected from explosions.
2. Robotic demining systems: These autonomous robots are equipped with sensors and manipulative systems that enable precise terrain scanning and mine removal without the need for human operators in the risk zone.
3. Minefield clearing machines: These machines are designed for rapid clearing of large areas contaminated by mines, employing a combination of techniques such as sweeping, demolition, or removal of mines.

The advantages of technology and demining machines are:

1. Safety: The use of demining machines reduces the risk of injury or death for deminers, as operators do not need to physically approach the mines.
2. Efficiency: Machines facilitate faster and more effective mine removal, contributing to the quicker release of affected areas.
3. Precision: Some systems, such as robotic demining machines, offer high precision in detecting and deactivating mines.

Disadvantages of technology and demining machines are:

1. Costs: The acquisition, maintenance, and operation of demining machines can be expensive.
2. Terrain limitations: Certain terrains may be difficult for machines to access, which can limit their effectiveness.
3. Technical challenges: Technical issues or failures may occur during the operation of demining machines, necessitating additional time and resources for repairs or replacements.

7. Demining machines in Humanitarian Mine Action (HMA)

Machines are utilized in humanitarian mine action (HMA) for two primary purposes:

1. To improve the safety of demining personnel.
2. To accelerate the land clearance process.

Since there are no established minimum competencies for individuals operating demining machines according to the International Mine Action Standards (IMAS), it is the responsibility of each organization to ensure comprehensive training and deployment protocols.

This section addresses the use of a specific range of machines but should be expanded whenever a machine not covered is intended for use in potentially hazardous areas. To ensure the proper utilization of each machine, all personnel involved in task assessments must be well-informed about the optimal operating conditions of the machine, its limitations, and constraints in application. This knowledge will enable task planners to select the most appropriate machine or combination of machines and tools to achieve the most efficient results.

Mechanical demining involves the use of machines in potentially hazardous areas during demining operations. This may include a single machine with one tool, one machine with multiple tools, or multiple machines with different tools. Machines with proven effectiveness are employed to prepare the area and provide armored protection for personnel. Area preparation machines are designed to enhance the efficiency of demining operations by removing vegetation, exposing hazards, or preparing the ground surface. In some instances, they may relocate the surface soil for searching and clearance in another area. Although these machines can detonate some hazards, they are not intended to eliminate all explosive threats. Machines designed to disturb the soil to a certain depth and neutralize all explosive hazards using tools such as rotating cutters or flails often fail to fulfill their intended purpose. However, they can still be useful for preparing breakthroughs or large areas when necessary.

Mine-Protected Vehicles (MPVs) are specifically designed to protect occupants from mine detonations. When equipped with appropriate wheels, they may attempt to detect certain hazardous areas by detonating pressure-activated or movement-sensitive hazards beneath the steel wheels, although this method is unreliable and generally not approved. MPVs can also be outfitted with extensive arrays of metal detectors mounted on the front or rear. Detected signals must be confirmed and investigated manually. Given the current technology, the effectiveness of MPVs is limited, and they should only be used if available at minimal or no cost.

Demining machines can be used for:

- removing vegetation prior to manual clearance or search with Mine Detection Dogs (MDD);
- preparing the ground for manual searching and clearance;
- assisting in locating hazardous areas by detonating one or more pressure-activated or movement-sensitive threats in the area;
- excavating soil and relocating it for search purposes;
- building trust among land users where there is No Threat Evidence (NTE), thereby eliminating the need for actual search and clearance operations.

In general, when a threat has been detonated, the demining machine should not be used to deliberately detonate other threats in that area. This is because the machine may disrupt any existing pattern and scatter or bury threats in a manner that increases risk for deminers and prolongs the time required for manual search and clearance. The demining machine can be used to approach suspicious hazardous areas in other locations to attempt to confirm the direction and extent of any present pattern of pressure/movement-sensitive threats.

7.1 Categorization of demining machines

IMAS 09.50 classifies demining machines into three categories: mine clearance machines, land preparation machines, and mine-protected vehicles. The category is determined by the primary use of the machine:

1. Mine removal machines: These machines are designed to destroy mines. They are equipped with tools suitable for this task, such as flails, cutters, screens, rollers, or a combination of these tools.
2. Land preparation machines: These machines are intended for removing vegetation or other obstacles to prepare the area for subsequent clearance activities.
3. Mine-protected vehicles: These vehicles are used as platforms for detection systems in Suspected Hazardous Areas (SHA).

For a comprehensive list of mechanical demining equipment and examples of various machines, refer to the GICHD Mechanical Demining Equipment Catalogue 2008. Annex A in this catalogue provides a summary of tasks typically associated with each category. There is some overlap between the tasks of these three categories.

Demining machines are primarily used in four roles:

1. Destroying mines.
2. Preparing land (and possibly destroying mines, though not always).
3. Confirming the presence of mines.
4. Serving as a platform for other tools or applications.

Some demining machines may simultaneously serve multiple purposes. For example, a machine with a ground-engaging tool such as a flail can destroy mines, remove vegetation, and loosen soil during demining operations. If equipped with a magnet, the machine could also remove metallic debris and gather information about mines and explosive remnants of war (ERW) [1].

Machines can be further categorized into:

1. Weight classification (light, medium, or heavy).
2. Invasive (designed to operate within Suspected Hazardous Areas - SHA).
3. Non-invasive (designed to operate from safe ground while "penetrating" into Suspected Hazardous Areas - SHA).
4. Remote-controlled (designed for remote operation from a safe distance).
5. On-board Control (designed to be operated by a driver/operator from a protected cabin).

7.2 Mine clearance machines

Mine clearance machines are designed for the detonation, destruction, or removal of landmines. For example, a front loader that is armored and modified for excavating mined soil qualifies as a mine removal machine, as the definition includes the removal of mines.

The primary types of mine removal machines include:

- Flails,
- Tillers,
- Machines with a combination of tools,
- Custom civil or military facilities for clearing or removing mines.

Figure 16. DOK-ING MV-10 Bison-flail system of demining

Figure 17. PT 300-D-tiller system of demining

7.2.1 Flails

Flail systems are the most common type of equipment for mechanical demining in the current market. They have a long history, with prototypes used in World War I and extensively during World War II. However, significant development of flail systems slowed until the early 1990s, when humanitarian demining spurred advancements in flail technology. More resources have been invested in research and development to improve flails than in any other demining system. Flails have evolved primarily due to market forces, with private engineering firms driving improvements for profit. National armies have also contributed to their development.

Figure 18. Flail wheel

The fundamental working principle of flails involves a rotating shaft, axle, or drum with lengths of chain links attached to their surface. These chains deliver powerful impacts to the ground when rotated at high speeds. Some flail designs are particularly effective against anti-tank mines. The distance of the chains from the flail unit's axle allows for a standoff that enables the explosion to somewhat dissipate before impacting the vehicle's chassis. However, flails are primarily considered effective tools against anti-personnel mines and small unexploded ordnance (UXO) [11].

Characteristics of flail wheel

The length of the chain striking the ground at a specific speed constitutes the basic operational methodology of all flail systems. The objective is to target the ground and/or the mines and unexploded ordnance (UXO) within it. The impact of the flail on the target is referred to as the flail strike. Three characteristics of the flail strike have been identified (Fig. 19): the disruptive strike, the detonation strike, and the ejection strike.

The disruptive strike occurs when the flail's impact physically damages a mine or UXO. In the worst-case scenario, the weapon remains functional but becomes more dangerous. Ideally, a disruptive strike will render the munition non-functional by shattering it. Fully functional mines can be disrupted by the flail, causing the detonation mechanism to fail. Additionally, some mines may already be non-functional before being struck. There is no known method to predict the ratio of functional to non-functional mines that will be disrupted.

The detonation strike occurs when the flail's impact triggers the detonation of a mine or the ground above it by activating a series of detonators. This helps to reduce the area of contamination by immediately indicating the presence of mines. However, detonations are not always complete; sometimes the detonator activates, but the main charge of the mine does not explode, often due to moisture. These are referred to as partial detonations. Factors such as the type of mine, ground conditions, engine power, penetration capability, and the machine's forward speed affect whether a mine will detonate or be disrupted during flailing.

The ejection strike occurs when the flail's impact causes a mine to be lifted and ejected from the flail unit. Although ejections are relatively rare, they are likely caused by an incomplete impact of the chain link that lifts the mine, momentarily entangling it in the rotating chains before ejecting it forward or sideways. If a mine falls onto the path of the machine, it is likely to be detonated or broken upon a subsequent strike. However, mines thrown into previously cleared or non-suspicious areas create new suspicious zones. This issue raises significant concerns for critics of flail systems as primary tools for clearance. Nonetheless, improvements made by mechanical engineers have significantly reduced the occurrence of ejections in certain flail systems, according to field operators [1].

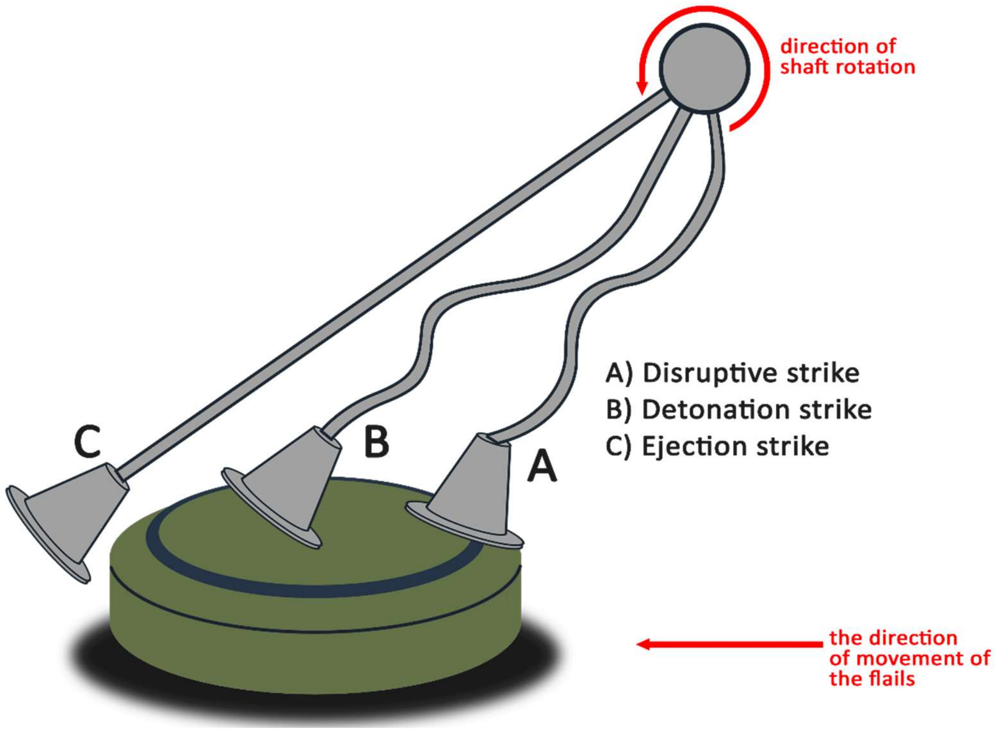

Figure 19.Types of flail system strikes

Effectiveness of the flail method

The overall efficiency parameter of flails is the centrifugal force exerted by the impact hammer and chain. This force is subordinate to the selection of chain length, but most importantly, it is influenced by the choice of the hammer head or type of impact hammer. Earlier in the text, we briefly outlined some of the types of impact hammers used in this method. The most effective type of impact hammer is the T-shaped design with a sharpened bottom edge (as shown in Fig 20). Figure 15 illustrates the forces exerted by the flail on the ground. From this depiction, we can see that this type of hammer, in a certain way, excavates the soil in front of the mine, leading to situations where the mine becomes uncovered and left exposed, which increases the risk, as the condition of the mine remains unknown. This is indeed one of the drawbacks of this demining system, particularly in soils with higher moisture content. The method can be improved by introducing additional hammers on longer or shorter chains or by combining it with other types of hammers, such as balls. Despite the existence of certain drawbacks, the flail method is highly effective in destroying mines, as evidenced by the images below [1].

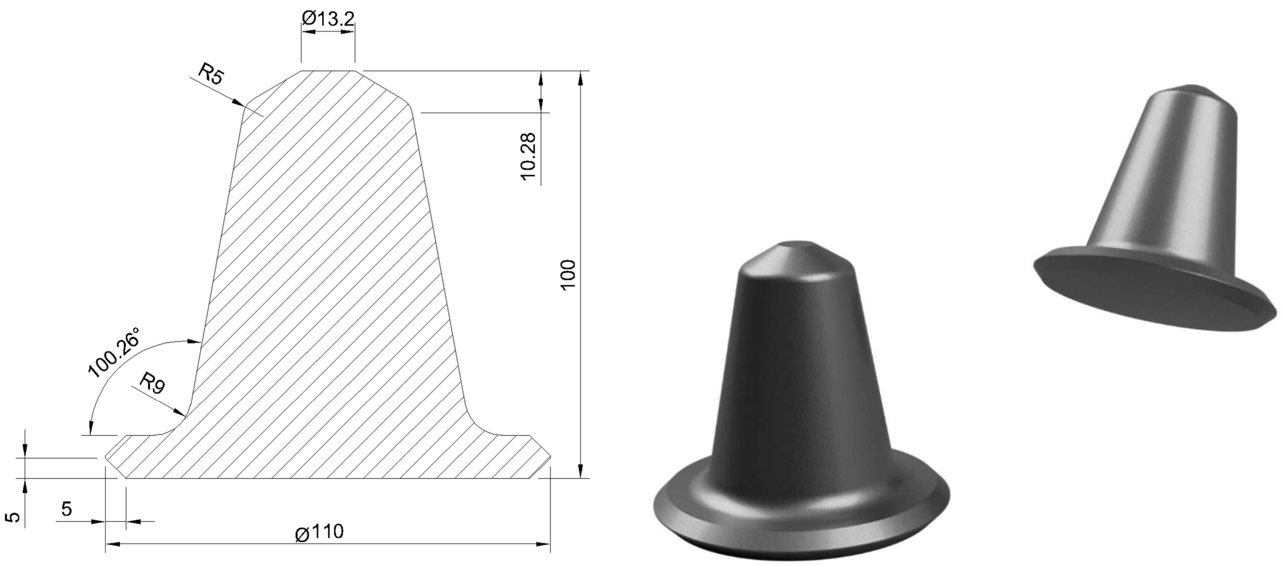

Figure 20. Type of flail chain head shape, most effective shape for landmine clearance, with technical data

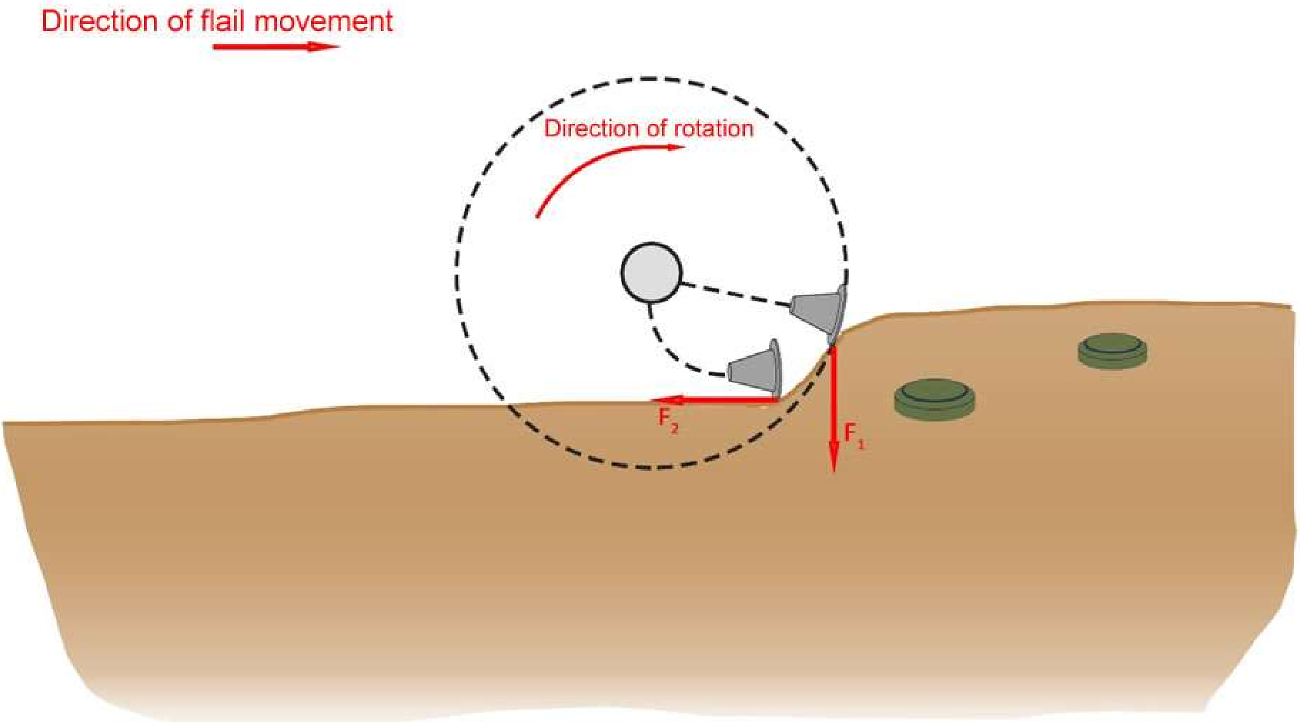

Figure 21. Flail forces acting on the ground

7.2.2 Tillers

The tiller system represents the second-largest family of specialized demining machines. Most mills are based on the chassis of a tank or forestry machine, which makes them heavy and large, although lighter designs are also emerging. A mill typically features a rotating drum with overlapping rows of alloy steel teeth or blades that grind and chew the soil to a selected depth. This process detonates or shatters anti-personnel mines, smaller unexploded ordnance (UXO), and sometimes even anti-tank mines.

Due to their size, mills can be challenging to operate in areas with poor infrastructure. However, when used correctly in suitable environments, these powerful machines effectively "brutalize" suspicious terrain, ensuring that few explosive devices escape destruction. Most milling systems are produced in Austria, Germany, and Sweden, with five manufacturers producing mills ranging from 14 to 53 tons. There are also combined systems, such as the STS MineWolf mill/flail (24.7 tons with a milling system) and the Redbus Mineworm, which is part of the Land Mine Detection System (LMDS) and weighs 15 tons.

Figure 22. Tiller

Characteristics of tiller

The tiller operates using sharp knives, teeth, or bits attached to a rotating drum powered by a heavy-duty motor (high-torque electric motor). The milling unit directly penetrates the soil, extracting material to a depth ranging from 0 to 40 centimeters at the operator's discretion. This interaction with the ground and all the explosive devices within it is referred to as the "bite." Three characteristics of the mill's bite have been identified concerning their effects on mines/UXO, similar to those observed in the impact of flails. These are briefly discussed below (Fig. 23).

Disruptive bite

The disruptive bite occurs when the milling unit physically damages mines/UXO through contact with its bits. Explosive devices can be shattered to the point of becoming harmless or only partially functional, potentially becoming more unstable than before.

Mines/UXO are likely to be disturbed if their fuses are non-functional (i.e. if they are defective) or if the angle of attack of the mill prevents direct contact with the fuse, causing the casing to rupture before the explosive devices can function properly. Disruptive bites result in a positive outcome when the explosive devices are sufficiently broken to no longer pose a threat.

Detonating bite

The detonating bite refers to the destruction of explosive devices through detonation. When the mill strikes a mine/UXO or exerts pressure, particularly on hard ground, it can activate the fuse mechanism. Instances in which the fuse operates but the main charge does not detonate are considered partial detonations and fall under the category of detonating bites.

Ejecting bite

The ejecting bite occurs when a mine is lifted from its position in the ground and thrown to a new location. Similar to flails, this results in ejection. Ejecting bites from mills are rare, and when they do occur, the explosive devices are typically thrown in a line in front of the machine rather than to the side. Reports from the field suggest that ejecting bites from mills is less problematic compared to those from flails [1].

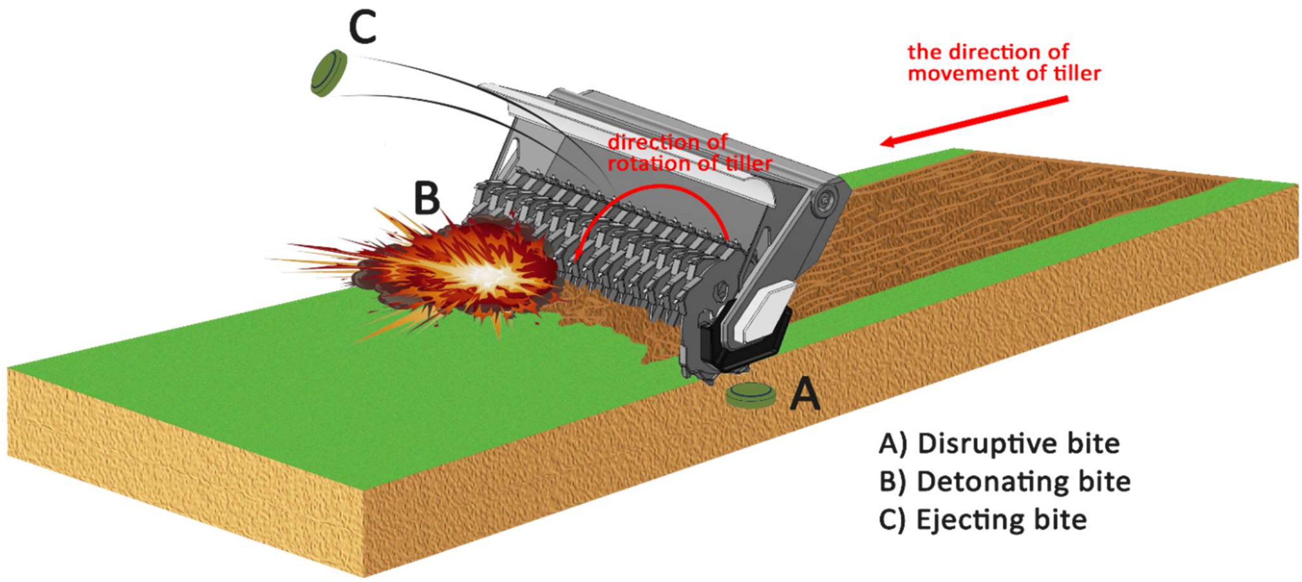

Figure 23. Types of tiller system bite

Effectiveness of the Tiller method

The design of the tiller is based on the principle of soil excavation and mine neutralization. The soil excavation mode demonstrates the relative rotation of the rotor in relation to the movement of the machine, indicating the direction in which the soil beneath the rotor is expelled. The counterclockwise mode of soil excavation is used to neutralize mines beneath the rotor, while the same direction is employed to neutralize mines in front of the rotor.

One of the disadvantages of this demining system is the potential damage to the tips of the mill (breakage of the spikes). This is due to the soil composition encountered by the machine, particularly when it comes across certain stones. In both cases, with the flail method and the milling method, the drawbacks are influenced by the soil composition on which the machines operate, making it difficult to implement preventive measures [1].

Figure 24. The most effective tiller shape for mine clearance

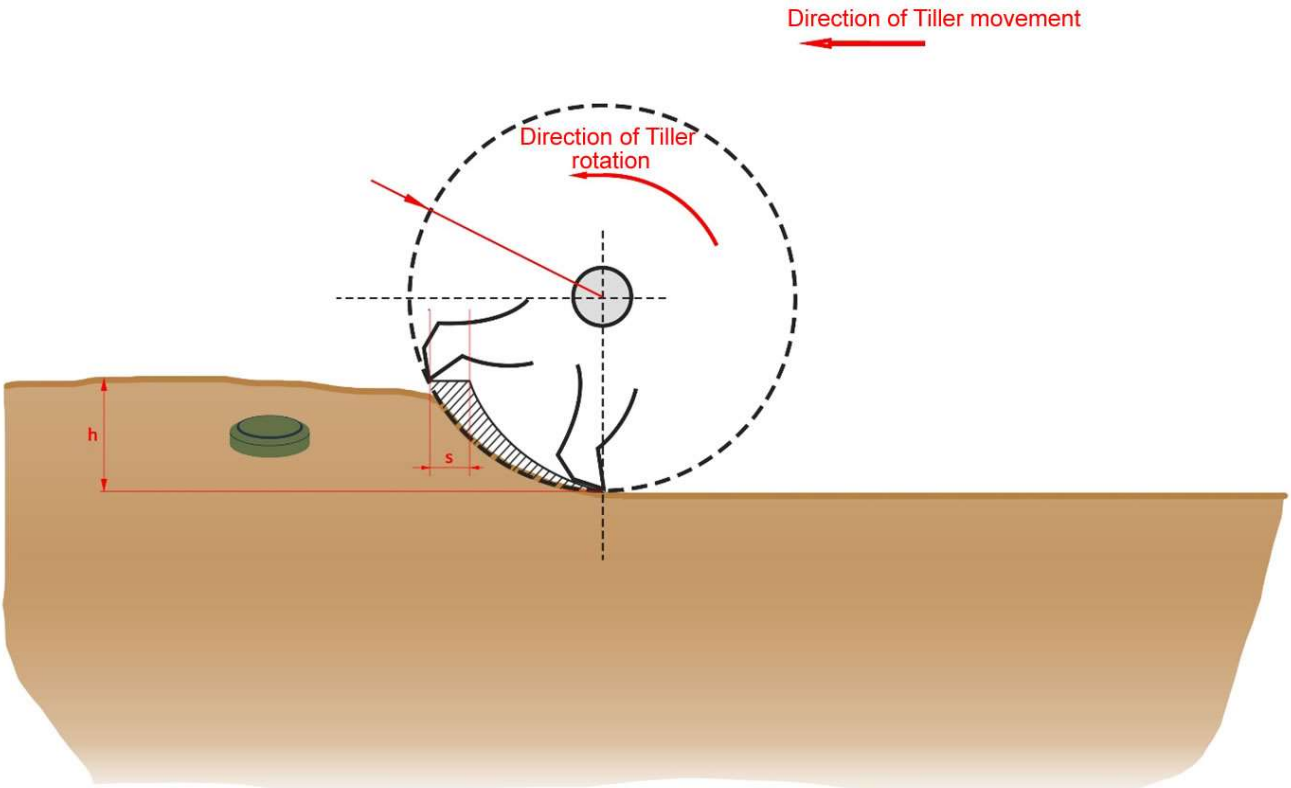

Figure 25. Tiller forces acting on the ground

7.2.3 The most effective method for landmine removal using the mechanical principle (independent positioning of flail and tiller)

The independent positioning of the flails and the milling cutter allows for different operational speeds and various excavation depths. For mine destruction, the primary role is assigned to the flail, as illustrated in the image below.

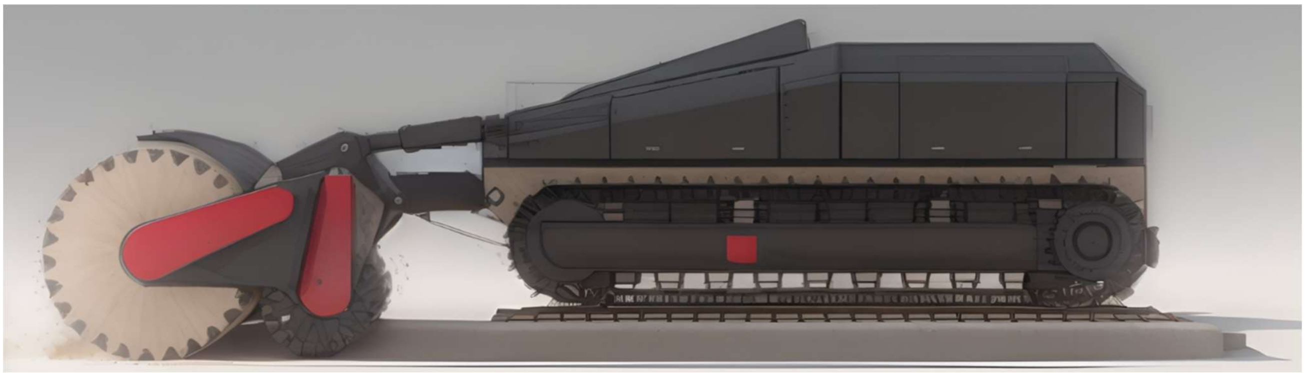

Figure 26. Demining Machine with Flail and Tiller System

The independent positioning and movement of the flails and milling cutter in relation to the excavation depth provides greater efficiency compared to the conventional arrangement with two flails. The combination of flails and milling cutters offers specific advantages when excavating different types of soil. Depending on the demining requirements, the excavation depth and the number of revolutions can be adjusted to achieve higher operational speed and better work efficiency. Each segment of the milling cutter can have multiple heads positioned at a relative angle of 120°. The segments are phased so that the cutting heads form three spirals that start from the center of the rotor and symmetrically extend outward on each side [1].

The destruction of high-power mines must be carried out with the primary tool - a flail with a large radius - that will not be damaged. The milling cutter, as a secondary tool, is adequate for adjusting the excavation depth and completely clearing mines.

In summary, the combination of the flail as the primary tool and the milling cutter as the secondary tool offers the following advantages:

- More flexible handling of different working conditions with two independent working tools.
- The ability to independently adjust the excavation depth and the number of revolutions of both the flail and the milling cutter.
- Adaptation to actual demining conditions.
- The two tools, the flail and milling cutter provide double efficiency.
- High reliability in destroying different types of mines.
- The flail destroys the most destructive anti-tank mines, avoiding significant damage to the machine.
- The milling cutter is lighter than the second flail, conserving material and engine power.
- The milling cutter destroys the smallest components.
- The milling cutter can be adjusted to determine the final excavation depth.

8. Conclusions

The persistent threat of landmines poses a significant global challenge, particularly in regions like Bosnia and Herzegovina, where decades of conflict have left vast areas contaminated and unsafe. The presence of these explosive remnants of war not only endangers civilian lives but also hampers socioeconomic development and the safe use of land for agriculture and habitation.

To address the complex problem of landmines, advanced detection technologies such as Ground Penetrating Radar (GPR) and Lidar systems offer promising solutions. These innovative detection methods enhance the ability to identify buried mines with high accuracy, reducing the risk to demining personnel and increasing the efficiency of clearance operations.

In conjunction with effective detection strategies, innovative concepts for mine destruction are essential. The combination of flail and tiller systems presents a powerful approach to the safe and thorough destruction of landmines. By integrating the destructive capabilities of flails, which excel at neutralizing various types of mines, with the precision of tillers, which can effectively prepare the terrain, this combined system maximizes operational efficiency and safety.

Such advancements in technology and methodology not only promise to expedite the demining process but also aim to ensure the safety of operators and communities affected by landmines. As we move forward, a multifaceted approach that incorporates cutting-edge detection tools and innovative destruction techniques will be crucial in mitigating the landmine threat and restoring safety and usability to affected regions like Bosnia and Herzegovina.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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